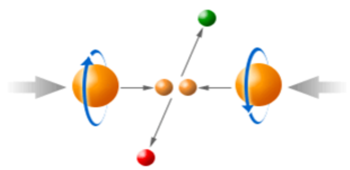


Accelerating Polarized Protons

Mei Bai

Collider Accelerator Department
Brookhaven National Laboratory

Outline

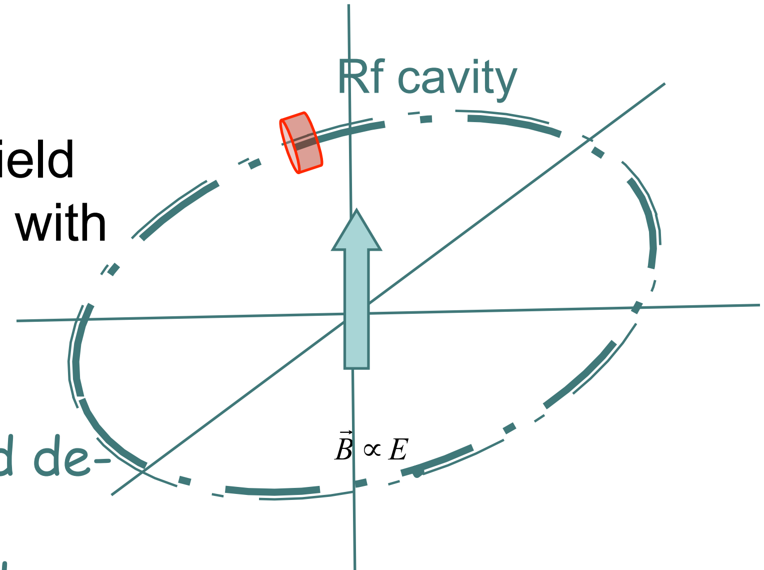
- General introduction of
  - accelerator physics
  - spin dynamics
- Accelerating polarized protons to high energy
  - Depolarizing mechanism
  - Techniques for preserving polarization
    - RHIC pp complex: the first polarized proton collider
- Other topics
  - Spin flipper
- Summary

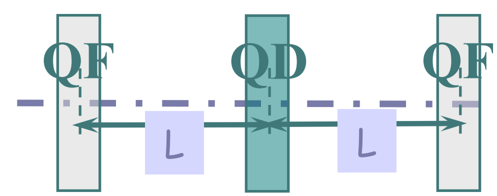
Suggested topics from Christine

- Basic accelerator physics
- Basics of polarized proton acceleration
- RHIC pp complex
- Is there any fundamental site requirements for polarized colliders. What should be considered if we can build from scratch?
- Why HERA didn't work
- Other than pp, what are the other species we can get in RHIC
- What are the required expertise for designing/ operating high energy colliders
- ….

Synchrotron

- The acceleration comes from the electric field with an oscillating frequency synchronized with the particle's revolution frequency
- Alternating gradient
  - *A proper combination of focusing and de-focusing quadrupoles yields a net focusing force in both horizontal and vertical planes*
- FODO cell: most popular building block for synchrotrons





$$\begin{pmatrix} x \\ x' \end{pmatrix}_2 = \begin{pmatrix} 1 & 0 \\ \frac{1}{-2f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{-2f} & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_1$$

Beam motion in a circular accelerator

- **Closed orbit**
  - A particle trajectory remains constant from one orbital revolution to the next
  - Closed orbit distortion: deviation from the center of the beam pipe

- **Betatron oscillation**
  - An oscillatory motion around the closed orbit from turn to turn

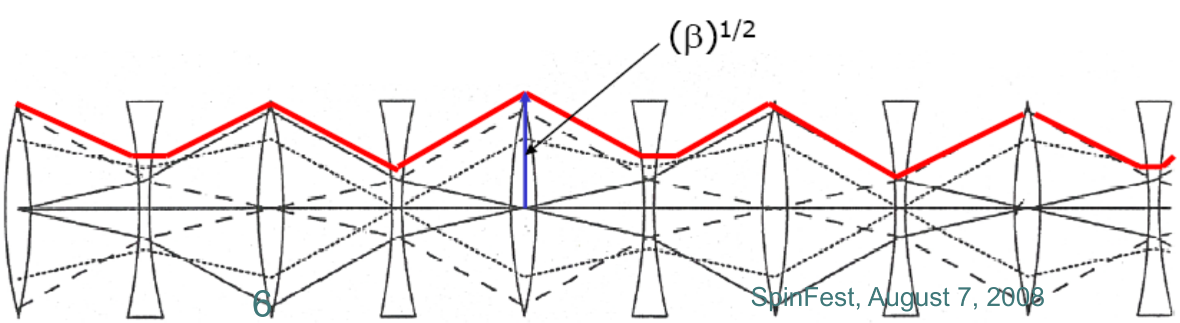
$$\frac{d^2x}{ds^2} + K_x(s)x = 0 \quad \Longrightarrow \quad x(s) = \sqrt{2\beta_x J}\cos(2\pi Q_x\theta(s) + \chi_x)$$

Particle motion in a synchrotron

- Betatron oscillation:

$$x(s) = \sqrt{2\beta_x J}\cos(2\pi Q_x \theta(s) + \chi_x)$$

- Betatron tune: number of betatron oscillations in one orbital revolution
- Beta function: the envelope of the particle's trajectory along the machine

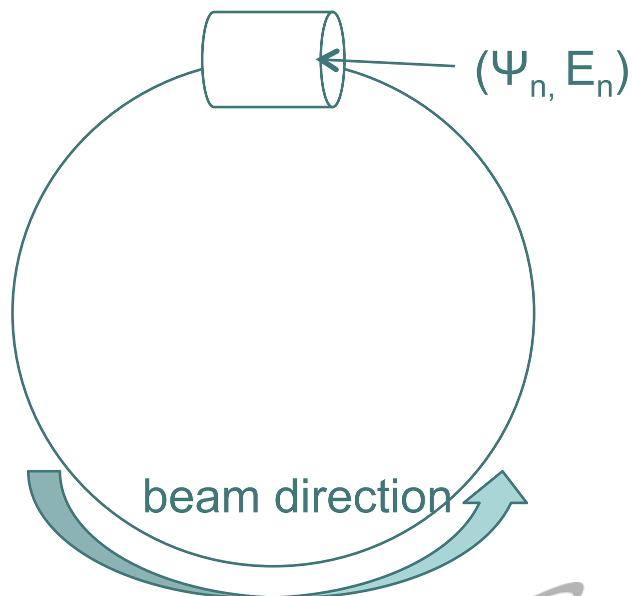


RF cavity

- Provide an oscillating electrical field to
  - accelerate the charged particles
  - keep the particles longitudinally bunched, i.e. focused
- A metallic cavity
  - resonating at a frequency integer multiples of the particle's revolution frequency

$$E_z(r,t) = E(r)\, e^{i2\pi f_{rf} t}$$

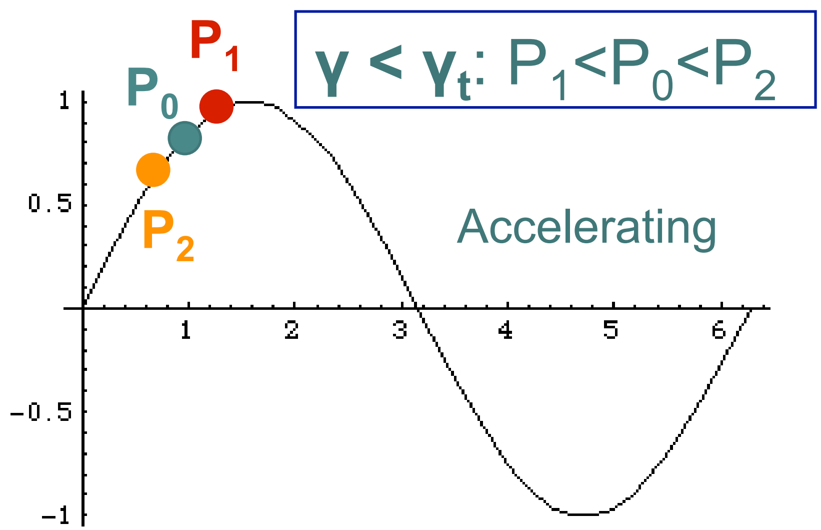
$$B_\theta(r,t) = B(r)\, e^{i2\pi f_{rf} t}$$

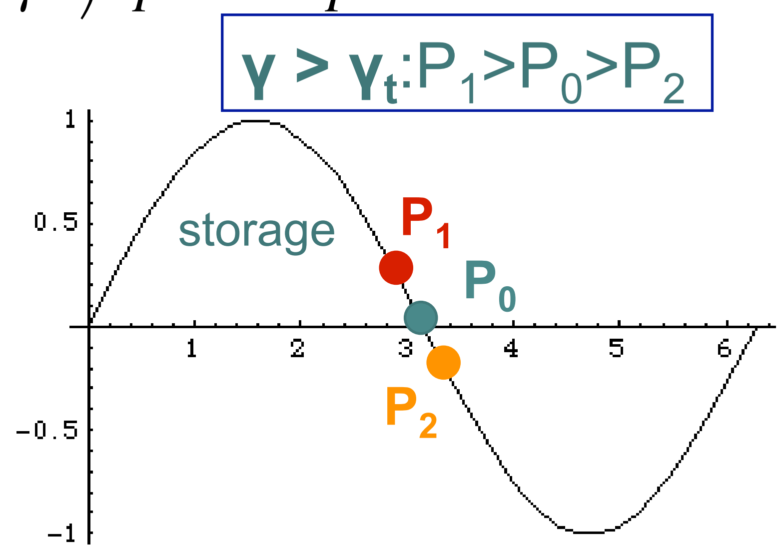


Longitudinal motion

- Synchronous particle: particle always arrive at the same phase of the oscillating electrical field
- Non-synchronous particle: particle which has different energy than the synchronous particle's

$$\frac{\Delta T}{T} = \frac{\Delta L}{L} - \frac{\Delta v}{v} = \left(\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \right) \frac{\Delta p}{p} = \eta \frac{\Delta p}{p}$$





Synchrotron motion

- Transition energy γ_t
  - When the particles are getting more and more relativistic, there is an energy when particles with different energies spend the same time to travel along the ring
  - Pre-determined by the optical structure of the accelerator
  - Synchronous phase has to jump 180° before and after the transition to keep the longitudinal stability

- Synchrotron oscillation

$$\phi_{n+1} = \phi_n + \frac{2\pi h\eta}{\beta_s^2 E}\Delta E_{n+1}$$

$$\Delta E_{n+1} = \Delta E_n + eV(\sin\phi_n - \sin\phi_s)$$

Spin motion: Thomas BMT Equation

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{e}{\gamma m}[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{//}] \times \vec{S}$$

Spin vector in particle's rest frame

Magnetic field along the direction of the particle's velocity

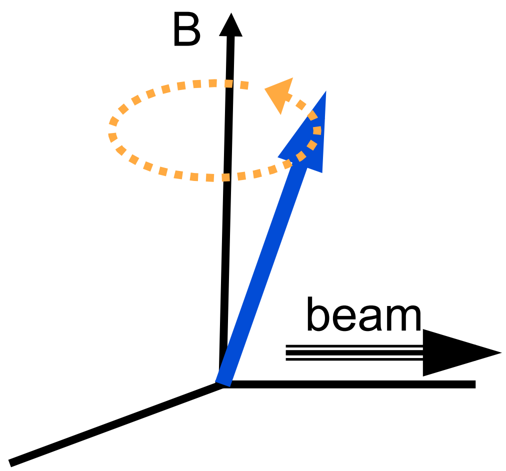
Magnetic field perpendicular to the particle's velocity

- G is the anomoulous g- factor, for proton,
  G=1.7928474
- γ: Lorenz factor

BROOKHAVEN
NATIONAL LABORATORY

Spin motion in a circular accelerator

- In a perfect accelerator, spin vector precesses around its guiding field along the vertical direction

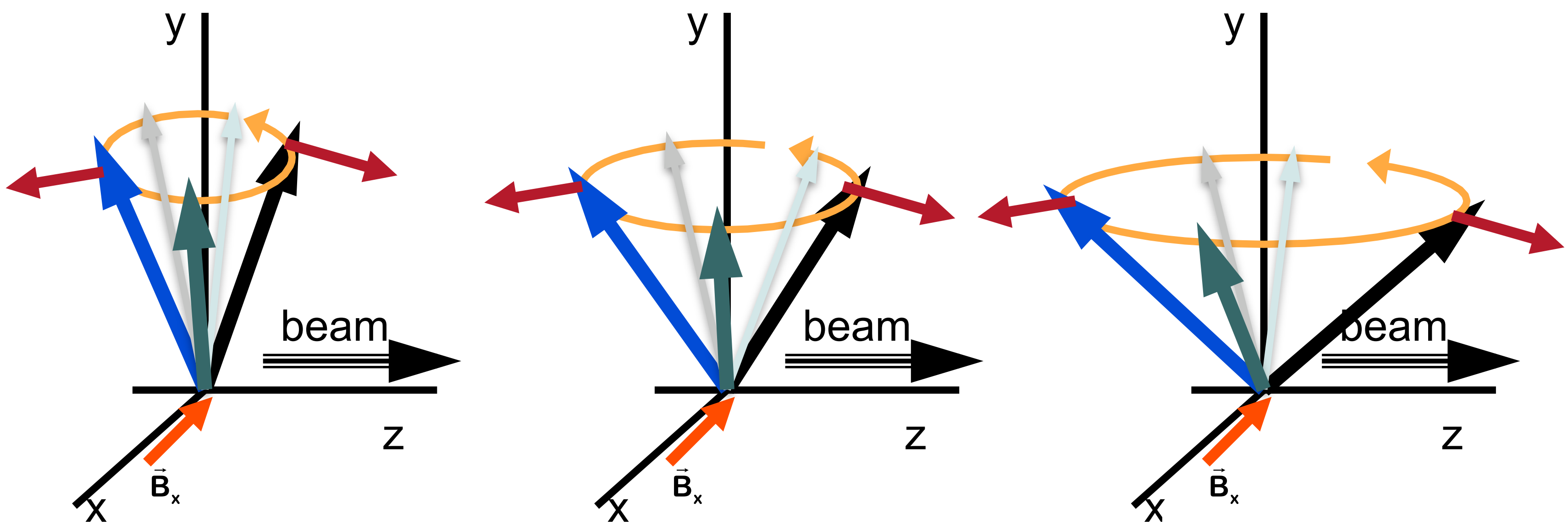


- Spin tune Q_s: number of precessions in one orbital revolution. In general,

$$Q_s = G\gamma$$

Depolarizing mechanism in a synchrotron

- **horizontal field kicks the spin vector away from its vertical direction, and can lead to polarization loss**
  - dipole errors, misaligned qadrupoles, imperfect orbits
  - betatron oscillations
  - other multipole magnetic fields
  - other sources



Initial

1st full betatron Oscillation period

2nd full betatron Oscillation period

Depolarizing resonance

- when the spin vector gets kicked at a frequency close to the frequency it processes. The location of a spin depolarizing resonance is at

$$Q_s = \text{ tune of the kick on the spin}$$

- For protons, imperfection spin resonances are spaced by 523 MeV

BROOKHAVEN
NATIONAL LABORATORY

imperfection spin resonance

- Source
  - dipole errors, quadrupole mis-alignments
- Resonance location:

$$G\gamma = k,\ k \text{ is an integer}$$

- Resonance strength:
  - Proportional to the size of the vertical closed orbit distortion

Intrinsic spin resonance

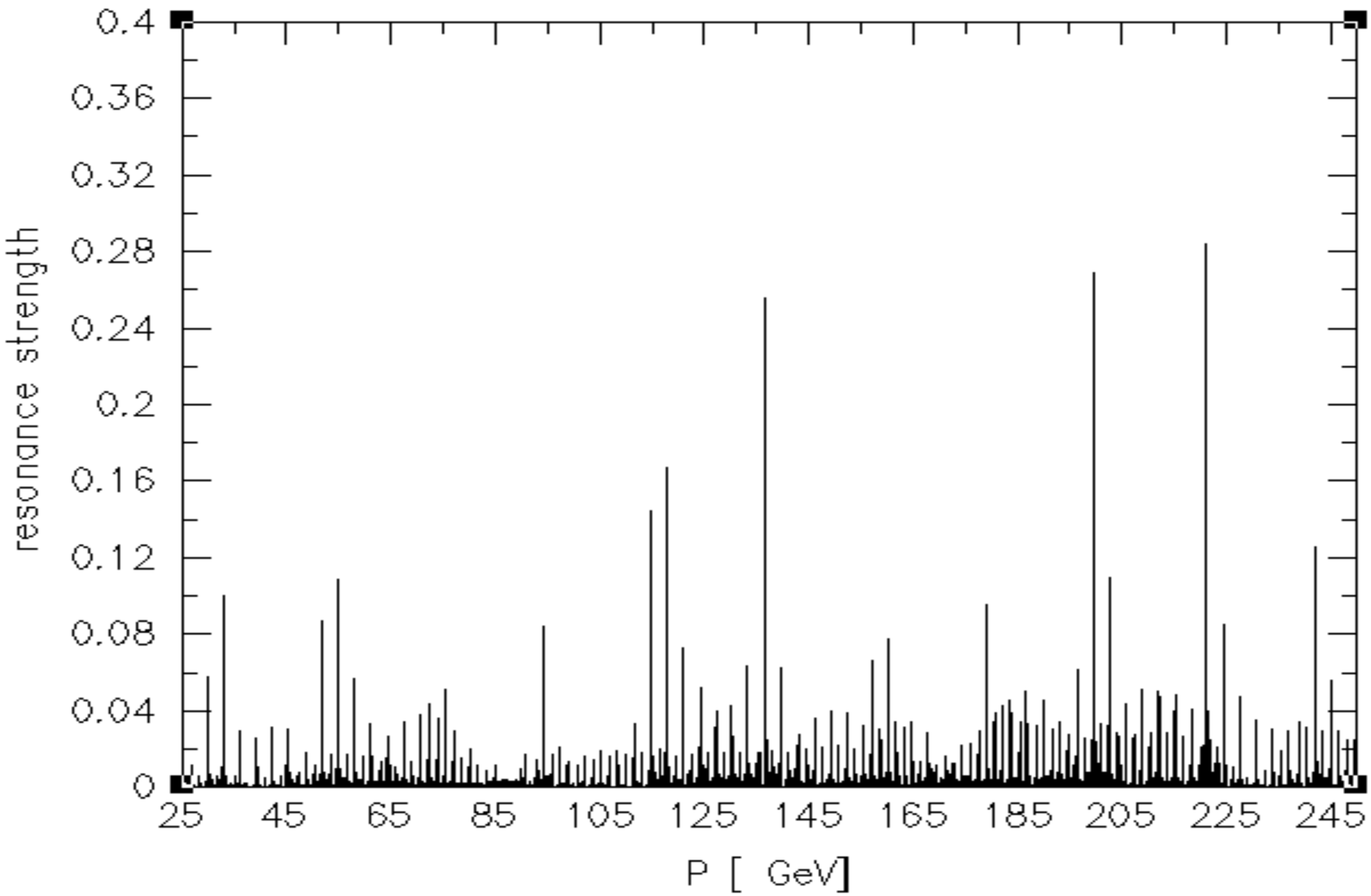
- Intrinsic resonance
  - Source: focusing field due to the intrinsic betatron oscillation
  - Resonance location:

$$G\gamma = kP \pm Q_y,$$

    P is the super periodicity of the accelerator, Qy is the vertical betatron tune

  - Resonance strength:
    - Proportional to the size of the betatron oscillation
    - When crossing an isolated intrinsic resonance, the larger the beam is, the more the polarization loss is

Spin depolarization resonance in RHIC



the higher energy, the stronger the resonance

Single resonance crossing

- Frossart-Stora formula

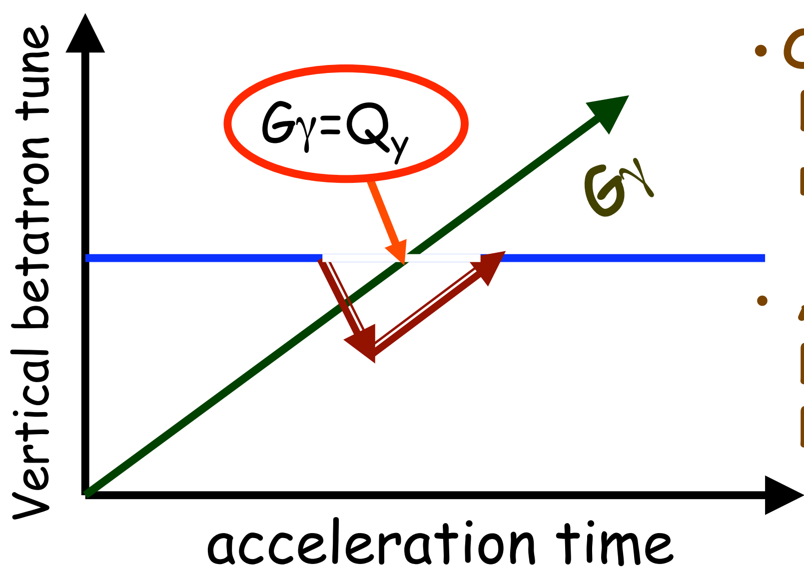
$$P_f = P_i \left(2e^{-\frac{\pi |\varepsilon|^2}{\alpha}} - 1 \right)$$

ε is the strength of the resonance.
α is the speed of resonance crossing

BROOKHAVEN
NATIONAL LABORATORY

overcoming spin depolarizing resonances techniques

- **Harmonic orbit correction**
  - to minimize the closed orbit distortion at all imperfection resonances
  - Operationally difficult for high energy accelerators
- **Tune jump**

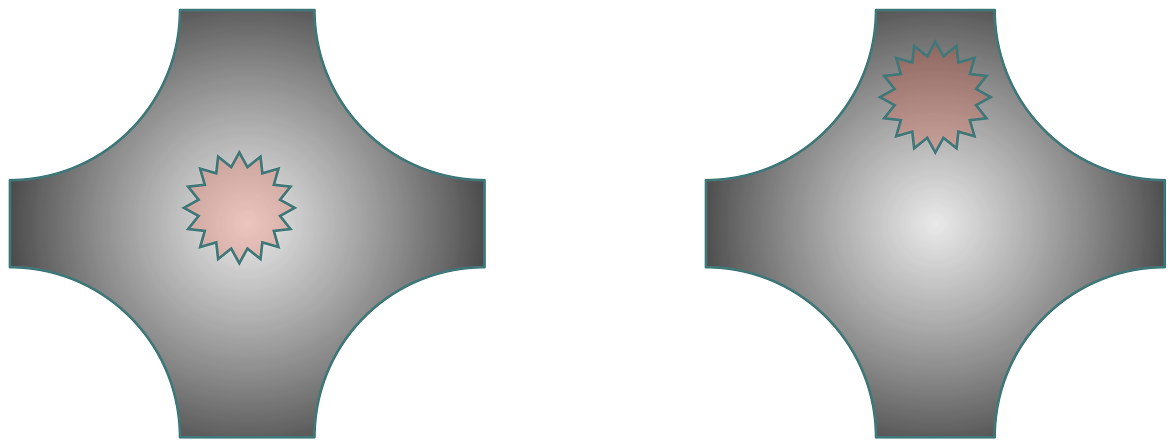


- Operationally difficult because of the number of resonances
- Also induces emittance blowup because of the non-adiabatic beam manipulation

overcoming spin depolarizing resonances techniques

- **AC dipole**
  - **Induce full spin flip by using an AC dipole to adiabatically excite a coherent betatron oscillation with large amplitude**

Quadrupole: horizontal Magnetic field linearly Proportional to the offset From magnet center



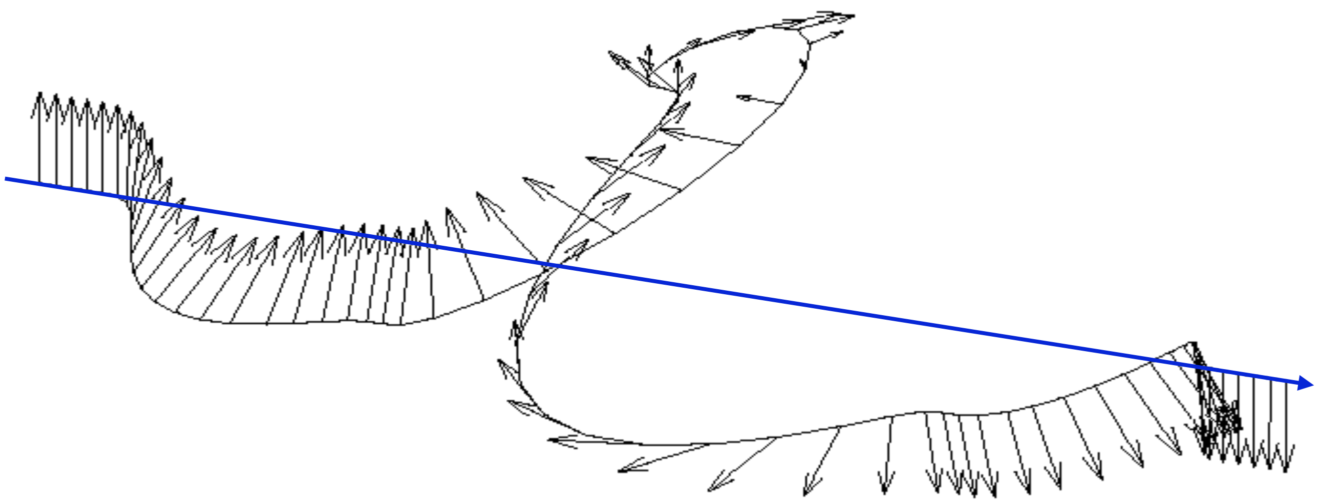
w.o. coherent oscillation With coherent oscillation

  - ***Can only correct strong intrinsic spin resonances***

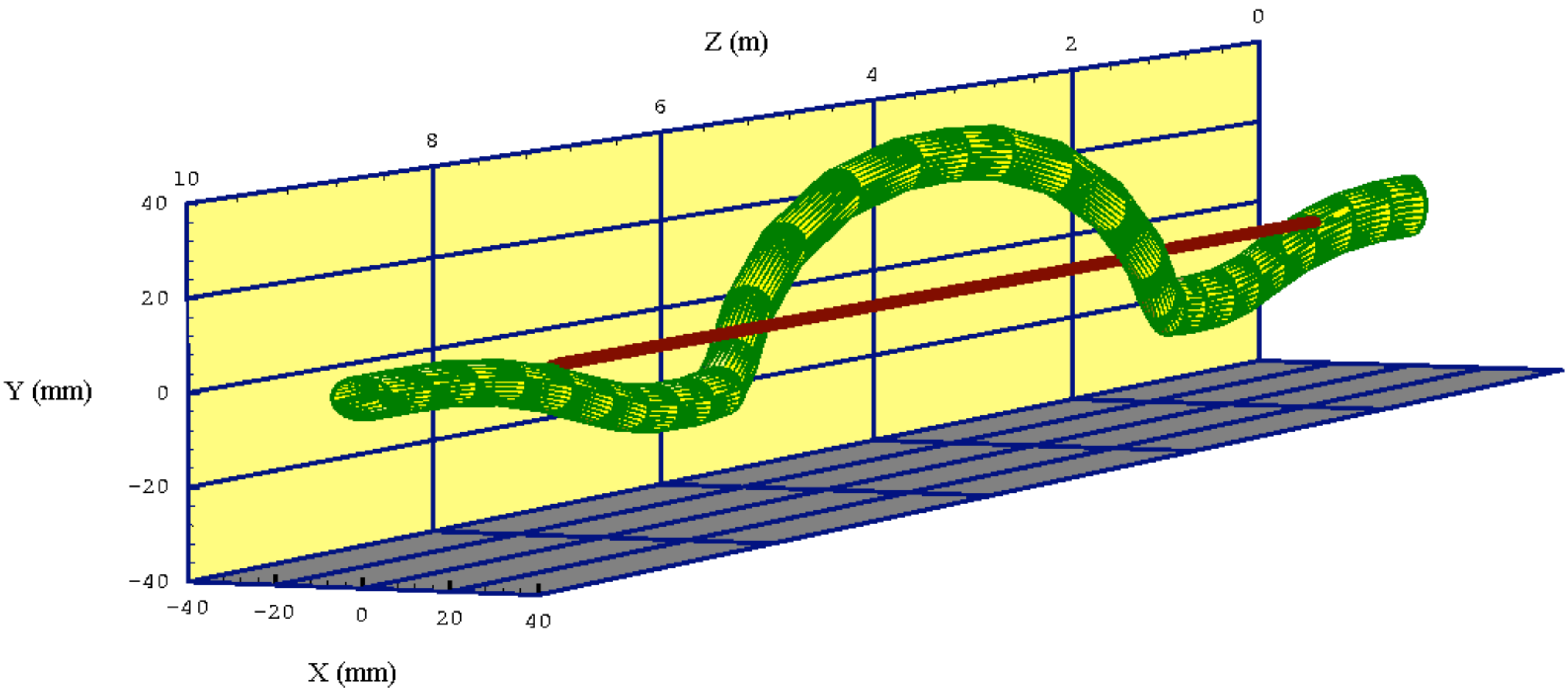
BROOKHAVEN NATIONAL LABORATORY

Innovative polarized proton acceleration technique: Full Siberian snake

- First invented by Derbenev and Kondratenko from Novosibirsk in late 1976
- A group of dipole magnets with alternating horizontal and vertical dipole fields
- rotates spin vector by 180°



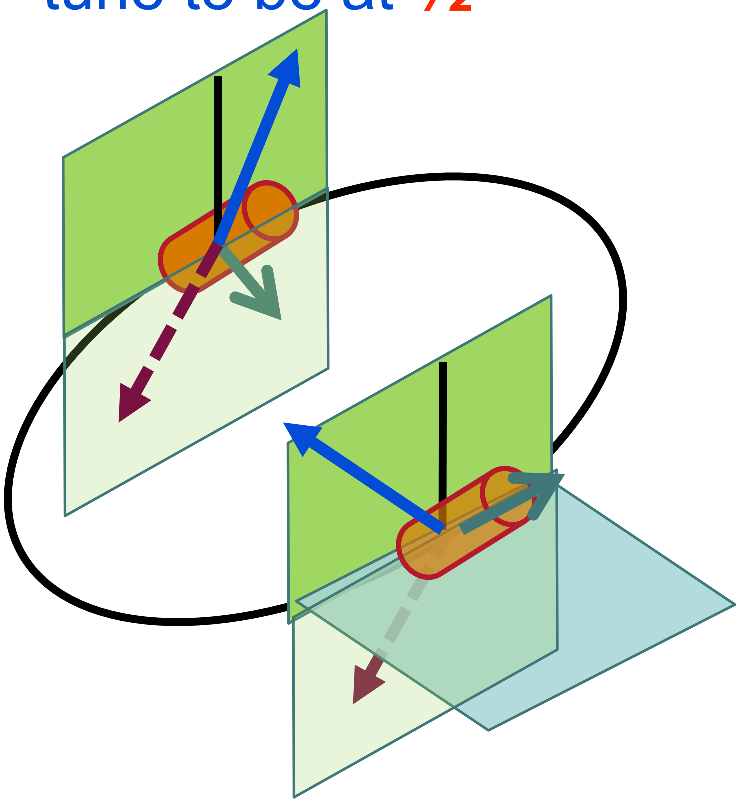
Particle trajectory in a Helical snake:



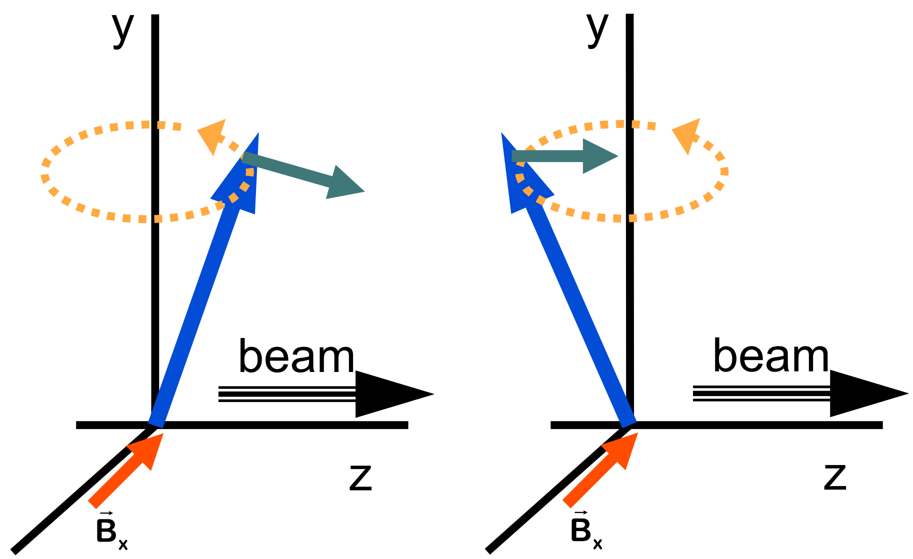
BROOKHAVEN
NATIONAL LABORATORY

Principle of full Siberian snake

- Use one or a group of snakes to make the spin tune to be at ½

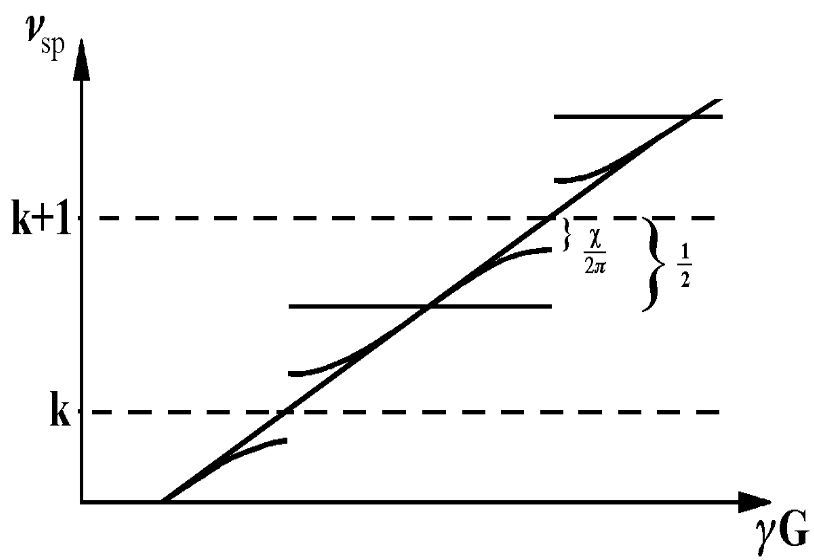


- Break the coherent build-up of the perturbations on the spin vector



partial Siberian snake: solution for medium energy accelerators

- rotates spin vector by an angle of ψ<180º
- Keeps the spin tune away from integer
- Primarily for avoiding imperfection resonance
- Can be used to avoid intrinsic resonance as demonstrated at the AGS, BNL.



$$\cos(\pi Q_s) = \cos(G\gamma\pi)\cos(\frac{\Psi}{2})$$

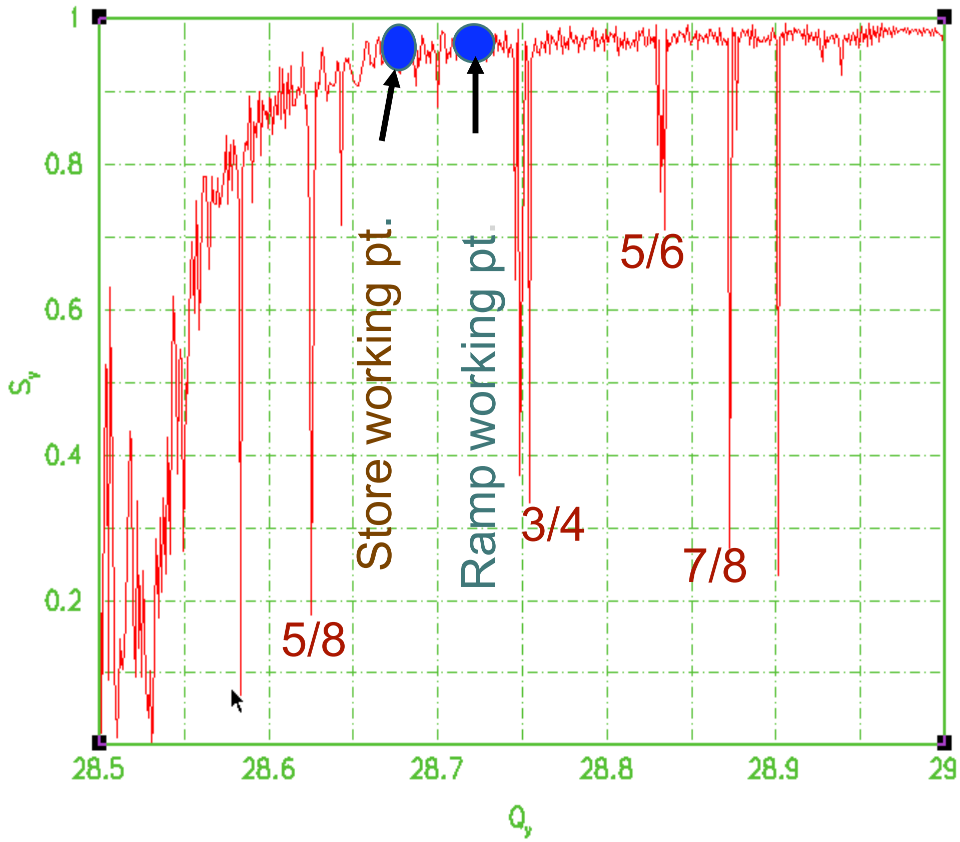
BROOKHAVEN NATIONAL LABORATORY

Snake depolarization resonance

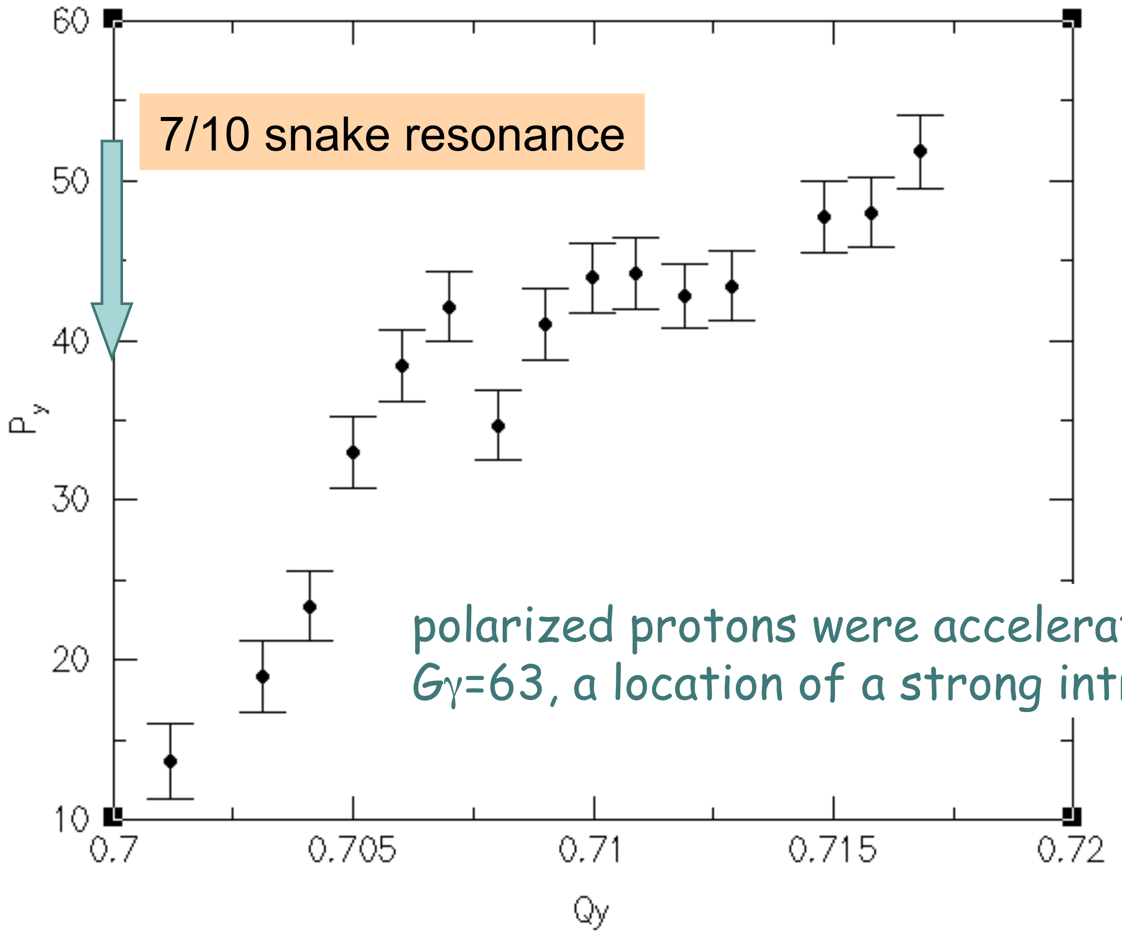
- Condition

$$mQ_y = Q_s + k$$

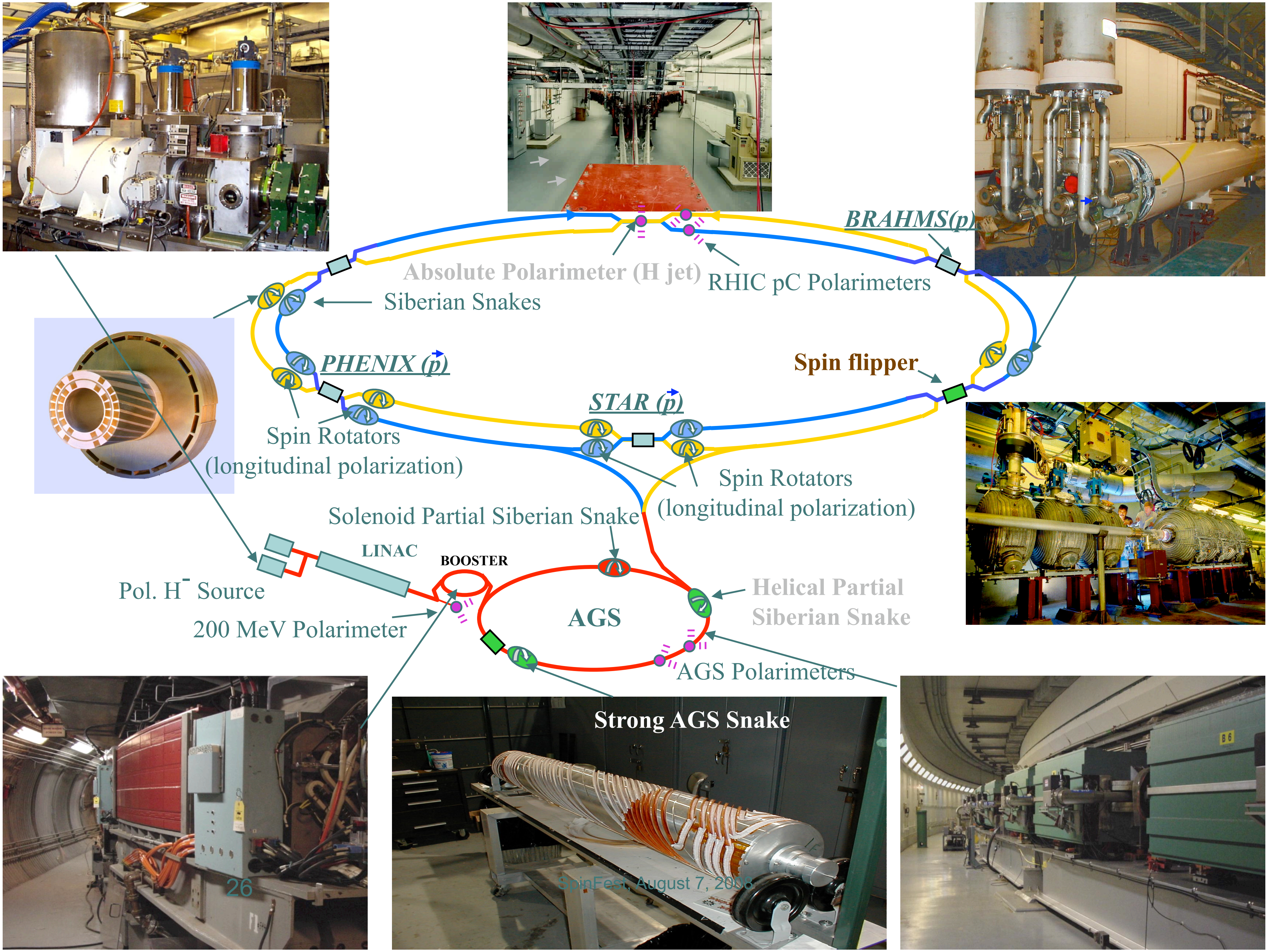
- even order resonance
  - When m is an even number
  - Disappears in the two snake case like RHIC if the closec orbit is perfect
- odd order resonance
  - When m is an odd number
  - Driven by the intrinsic spin resonances



Snake resonance observed in RHIC



polarized protons were accelerated to an energy of $G\gamma$=63, a location of a strong intrinsic spin resonance


BRAHMS(p)
Absolute Polarimeter (H jet)
RHIC pC Polarimeters
Siberian Snakes
PHENIX (p)
Spin flipper
STAR (p)
Spin Rotators
(longitudinal polarization)
Spin Rotators
(longitudinal polarization)
Solenoid Partial Siberian Snake
LINAC
BOOSTER
Pol. H⁻ Source
200 MeV Polarimeter
AGS
Helical Partial
Siberian Snake
AGS Polarimeters
Strong AGS Snake

Polarized proton setup in the Booster

❑ Booster

- Kinetic Energy: 200MeV ~ 1.42 GeV

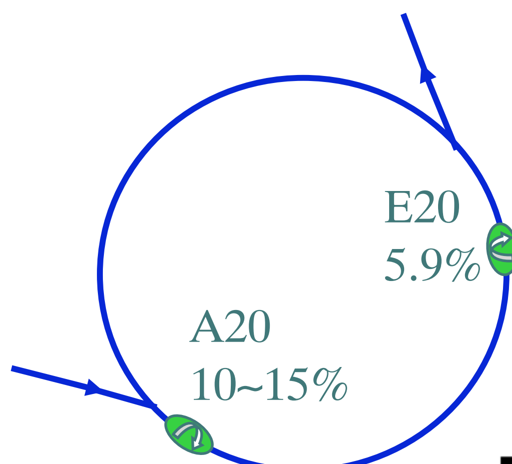
- Intrinsic spin resonances are avoided by setting the vertical betatron tune above the spin precession tune at extraction

- A total of 2 imperfection resonances and they are corrected by the harmonic correction of the vertical closed orbit closed orbit

Polarized proton setup in the AGS

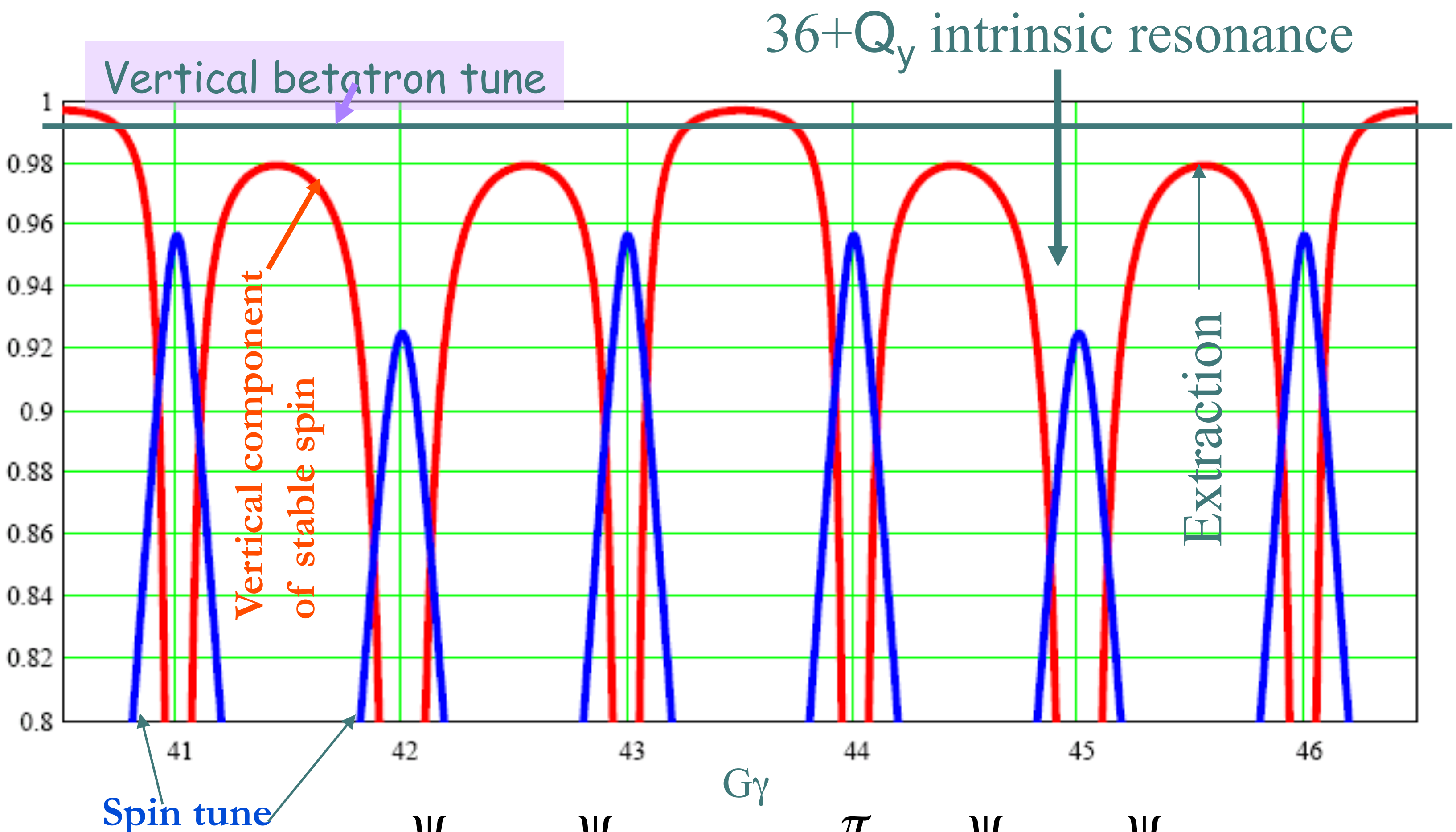
- **AGS (Alternating Gradient Synchrotron)**
  - Energy: 2.3 GeV ~ 23.8 GeV
  - A total of 41 imperfection resonances and 7 intrinsic resonances from injection to extraction
    - **One 5.9% partial snake plus one 10~15% partial snake**

$$\cos\pi Q_s = \cos G\gamma\pi \cos\frac{\Psi_1}{2}\cos\frac{\Psi_2}{2} - \cos G\gamma\frac{\pi}{3}\sin\frac{\Psi_1}{2}\sin\frac{\Psi_2}{2}$$



Courtesy of T. Roser

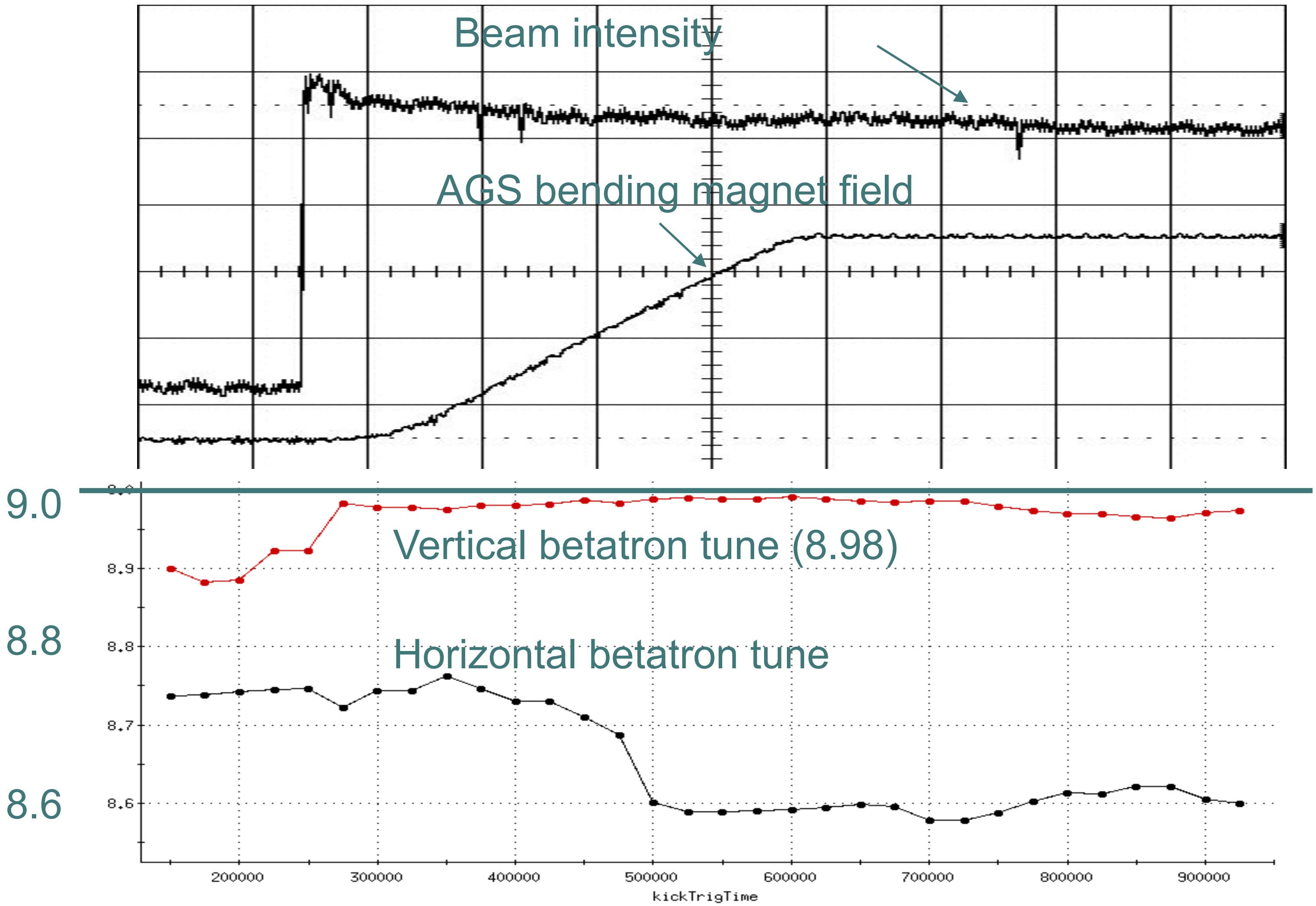
Spin tune with two partial snakes



$$\cos\pi Q_s = \cos G\gamma\pi \cos\frac{\Psi_w}{2}\cos\frac{\Psi_c}{2} - \cos G\gamma\frac{\pi}{3}\sin\frac{\Psi_w}{2}\sin\frac{\Psi_c}{2}$$

BROOKHAVEN NATIONAL LABORATORY

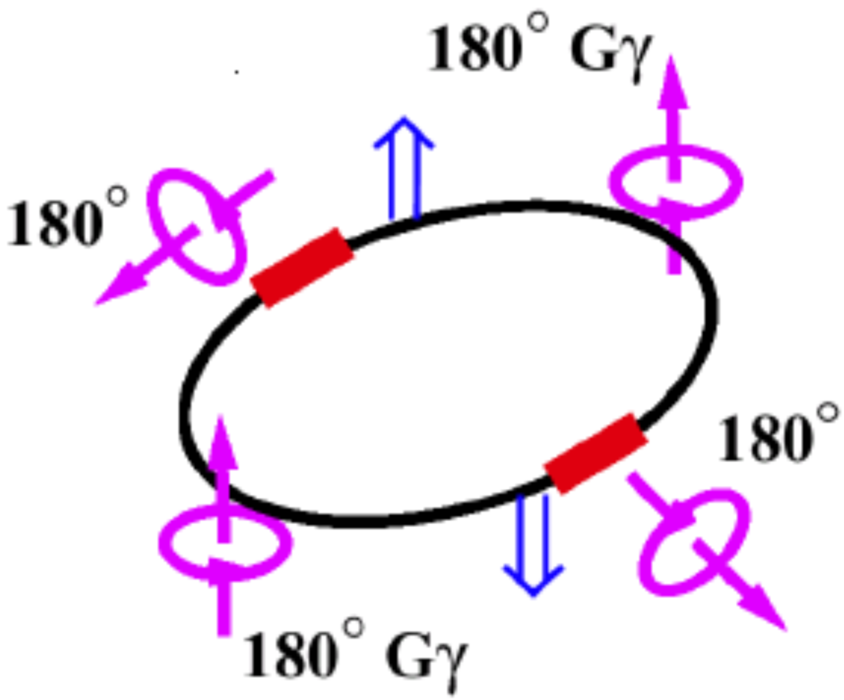
Polarized protons in the AGS



Courtesy of L. Ahrens and K. Brown

Polarized proton acceleration setup in RHIC

- Energy: 23.8 GeV ~ 250 GeV (maximum store energy)
  - A total of 146 imperfection resonances and about 10 strong intrinsic resonances from injection to 100 GeV.
    - **Two full Siberian snakes**

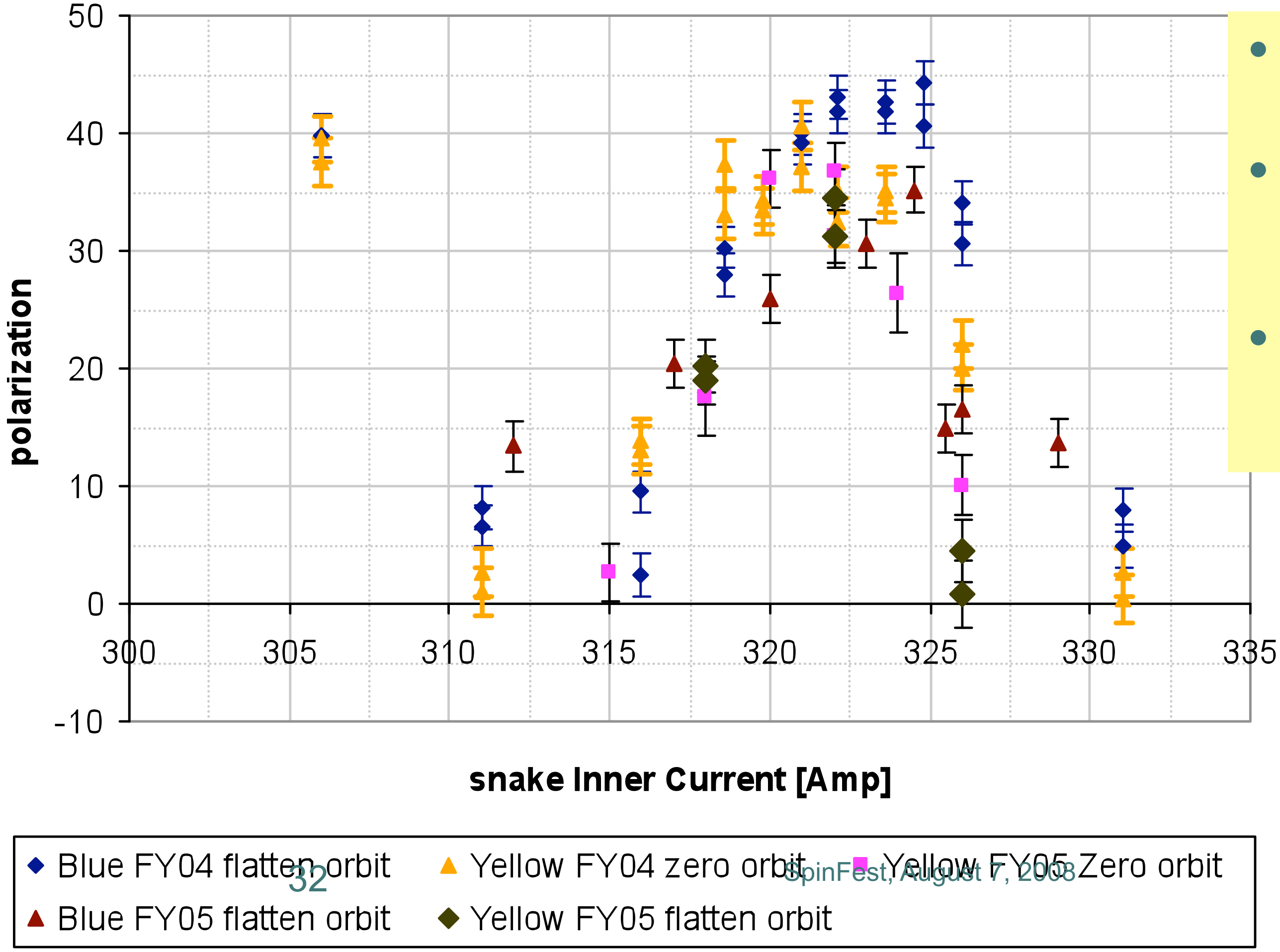


$$Q_s = \frac{1}{\pi}\left|\varphi_1 - \varphi_2\right|$$

$$\Rightarrow Q_s = \frac{1}{2}$$

How to avoid a snake resonance

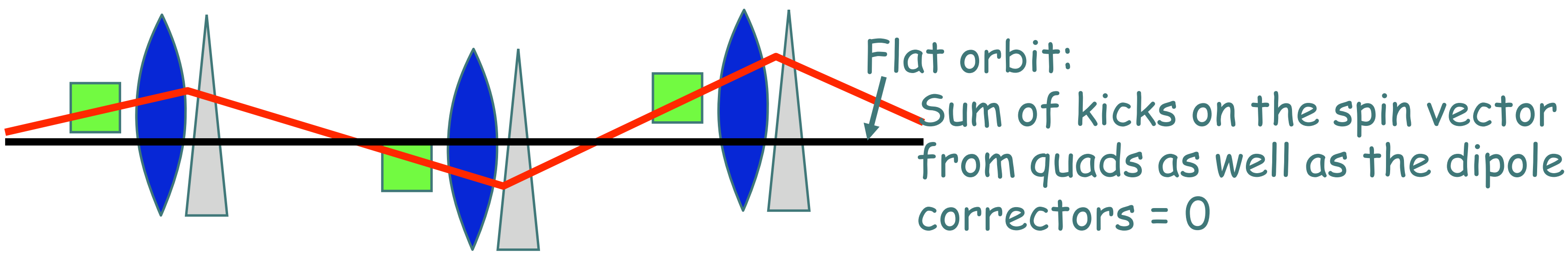
- Keep the spin tune as close to 0.5 as possible
  - snake current setting



- set the vertical tune to 0.745
- measure the beam polarization with different snake current
- expect no depolarization if the corresponding spin tune is very close to 0.5

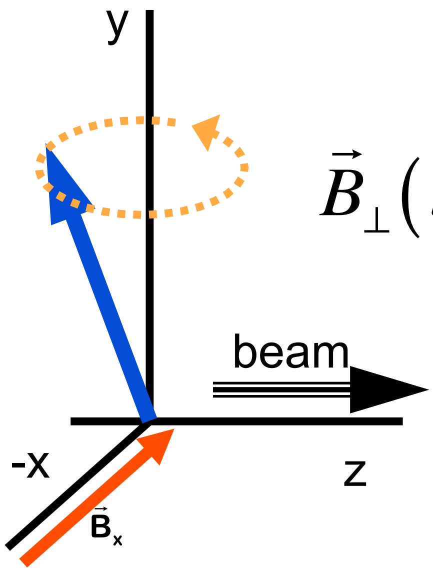
How to avoid a snake resonance

- Keep the vertical closed orbit as flat as possible

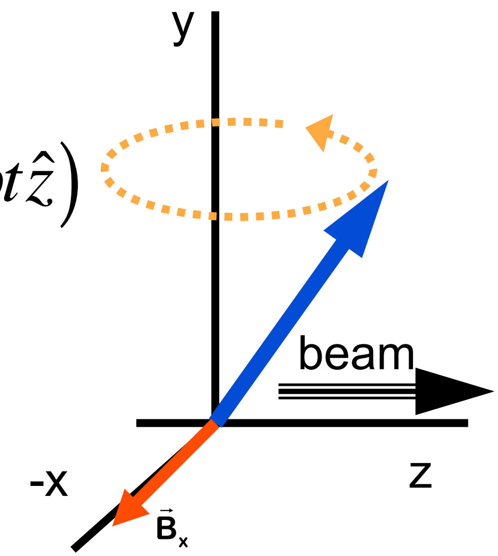


- Keep the betatron tunes away from snake resonance locations
  - Precise tune control

spin flipper



$$\vec{B}_{\perp}(t) = B_0\left(\cos\omega t\,\hat{x} + \sin\omega t\,\hat{z}\right)$$

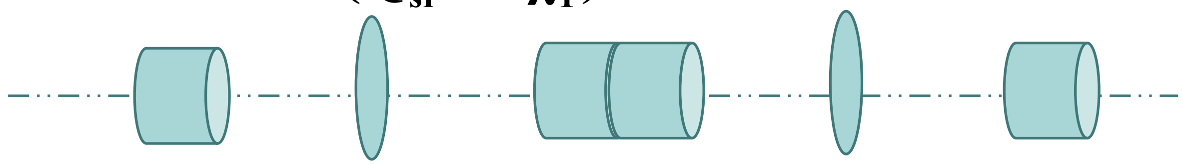


- In reality, a single rf dipole/solenoid with oscillating field strength is used to achieve full spin flip by slowly ramping its frequency cross the beam spin precession frequency
- Challenge for RHIC spin flipper
  - spin tune at ½ and single rf dipole/solenoid drives two spin resonances and no more single resonance crossing

RHIC spin flipper

Ac dipole 1:
$\Delta BL\cos(Q_{sf}\theta + \chi_1)$

Ac dipole 2:
$\Delta BL\cos(Q_{sf}\theta + \chi_2)$



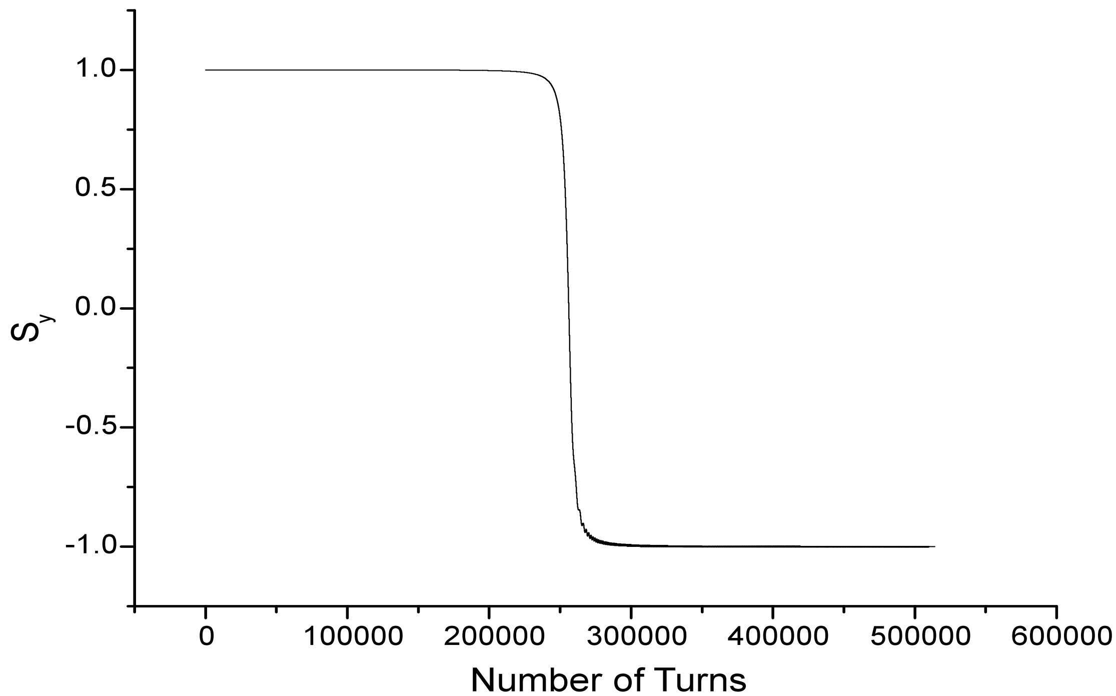
Spin rotator 1:
Axis: vertical
Angle $\psi_0/2$

Spin rotator 0:
Axis: vertical
Angle ψ_0

Spin rotator 2:
Axis: vertical
Angle $-\psi_0/2$

$$\boxed{\chi_1 - \chi_2 = 180^o + \psi_0}$$

Simulation



- Single particle with spin tune = 0.5
- Spin flipper:
  - Amplitude: 20 Gauss-m
  - Tune: 0.49 -> 0.51
  - Sweep in half million turns

BROOKHAVEN NATIONAL LABORATORY

Summary

- What have been covered in this talk
  - Some general accelerator physics and spin dynamics concepts
    - Synchrotron, betatron osicllation, synchrotron oscillation
    - Spin tune
    - Intrinsic spin resonance
    - Imperfection spin resonance
    - Siberian snake
    - Snake resonance
  - RHIC polarized proton complex
  - How Spin flipper works

Summary

- What's not covered in this talk
  - Can we have other polarized beams in RHIC?
    - Polarized helium: okay
    - Polarized deuteron: snake too weak. AC dipole?
  - What kind of expertise is needed for collider design and operation?
    - Accelerator physics: lattice design, simulation, …
    - RF engineering: RF cavity, …
    - Electrical engineering: power supplies, beam instrumentation electronics, …
    - Mechanical engineering: magnet design, …
  - Why HERA pp didn't work? ….

Recommendations

- An introduction to the physics of high energy accelerator Physics: D. A. Edwards, M. J. Sypher
- Spin dynamics and Snakes in Synchrotrons: S. Y. Lee
- RHIC polarized protons design manual
- http://www.c-ad.bnl.gov/kinyip/SchedPhys glossary_and_facts.htm